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Increasing the Resistance of a NiCrBSi Coating to Heat Wear by Means of Combined Laser Heat Treatment

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Abstract. Testing of NiCrBSi coatings formed by gas-powder laser cladding and combined laser heat treatment, including laser cladding and high-temperature annealing, were conducted under conditions of sliding friction on the Kh12M steel according to the pin-on-disk scheme. The combined processing resulting in the formation of large carbides and chromium borides in the coatings is shown to increase their wear resistance by a factor of 1.8 at sliding velocities of 6.1 and 9.3 m/s, when there is significant frictional heating of the friction surfaces.

INTRODUCTION

The formation of high-strength and wear-resistant coatings is an effective way of enhancing the performance of worn and new machine parts affected by high contact loads and temperatures. Coatings made of Ni–Cr–B–Si alloys are widely used for improving the quality of products operating under conditions of severe heating (rolls and roller beds in hot-rolling mills, hot-forming dies, parts of heat exchanging apparatuses, turbines, solid-fuel boilers, etc.) [1]. However, heating to temperatures ranging between 700 and 1100 °C causes continuous softening and a noticeable decrease in the wear resistance of NiCrBSi plasma and laser coatings [2, 3]. In [2] a conclusion was made that the high-temperature use of NiCrBSi coatings is limited due to the degradation of their matrix at temperatures exceeding 700 °C.

The applicability of NiCrBSi coatings at high temperatures considerably extends the new phenomenon of increased hardness and wear resistance of laser-clad NiCrBSi coatings resulting from extra annealing at 1000 to 1075 °C, which was discussed in [4, 5]. Under annealing of the metastable structure of the laser-clad coating followed by cooling, the coating acquires a highly strong wear resistant skeleton formed by large chromium carbides and borides, which preserves its enhanced properties under heating up to the annealing temperature. Based on the discovered phenomenon, a method was developed to produce NiCrBSi coatings with extremely high (up to 1000 °C) heat resistance by combined laser heat treatment (RF patent No. 2492980) [5], involving laser cladding with additional high-temperature annealing. The proposed new approach to the formation of heat-resistant coatings by combined laser-thermal method (with high-temperature annealing of the clad coating) was applied to enhancing the wear resistance of nickel-based alloy specimens produced by an additive laser technique, namely, by direct laser material deposition [6] and to producing a coating strain-hardened by friction treatment with a sliding indenter [7].

However, in [4, 5, 7], the conclusion about the heat resistance of the coatings was based only on hardness and wear resistance measurements at room temperature after cooling from the annealing (tempering) temperature. The aim of this paper is to study the possibility of increasing the wear resistance of a NiCrBSi coating, under

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considerable friction heating induced by sliding friction at high (above 5 m/s) speeds, by combined laser heat treatment.

MATERIAL AND EXPERIMENTAL PROCEDURE

A self-fluxing NiCrBSi powder with the composition (wt%) 18.2% Cr, 3.3% B, 4.2% Si, 0.92% C, 2.6% Fe, the rest Ni was used for cladding. The powder was clad onto a steel plate (0.20% C) with the use of a CO_2 continuous laser, with a radiation power of 1.4 to1.6 kW, a speed of 160 mm/min, a powder consumption of 2.9 to 3.8 g/min, and a 6×1.5 mm laser spot on the surface. The powder mixture composed of 40 to 160 μm grains was transported to the zone of cladding by an inert gas (argon) under a pressure of 0.5 atm. In order to decrease surface stresses, the cladding was performed in two passes by overlaying one layer onto the other. The coating thickness after cladding and polishing was 0.9 to 1.3 mm. Some specimens were subjected to combined laser heat treatment consisting in cladding followed by annealing at 1025 °C (2 hour holding) with subsequent cooling in a vacuum furnace.

Microhardness was measured on a Shimadzu HMV-G21DT microhardness tester under a load of 0.49 N as an arithmetic mean of 10 measurements. The microstructure and the wear surfaces were examined with the use of a Tescan Vega II XMU scanning electron microscope equipped with a wave dispersive (Inca Wave 700) and energy dispersive (Inca Energy 450 XT) microanalyzer.

Tribological pin-on-disk tests were performed on a laboratory device (Fig. 1). The end surfaces (7×7 mm) of the clad specimens slided on a revolving Kh12M steel disk (microhardness 61.5 HRC) in air, with the load N=98 N. The average sliding velocities were V=6.1 m/s and V=9.3 m/s, the testing time being t=22 min and t=9.5 min respectively. The testing time was determined by the linear wear of the coating, which did not exceed 0.7 mm. We determined specimen mass loss during wear, the friction force (with the use of an elastic element – a ring with resistance strain gauge transducers pasted to it) and the average temperature in the surface layer of the specimen (by a chromel-alumel thermocouple with 0.2 mm diameter electrodes welded in at a distance of ~0.5 mm from the gauge surface of the specimen).

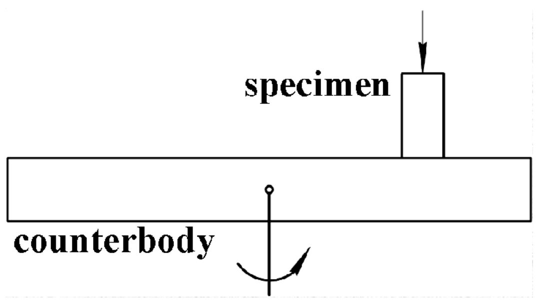


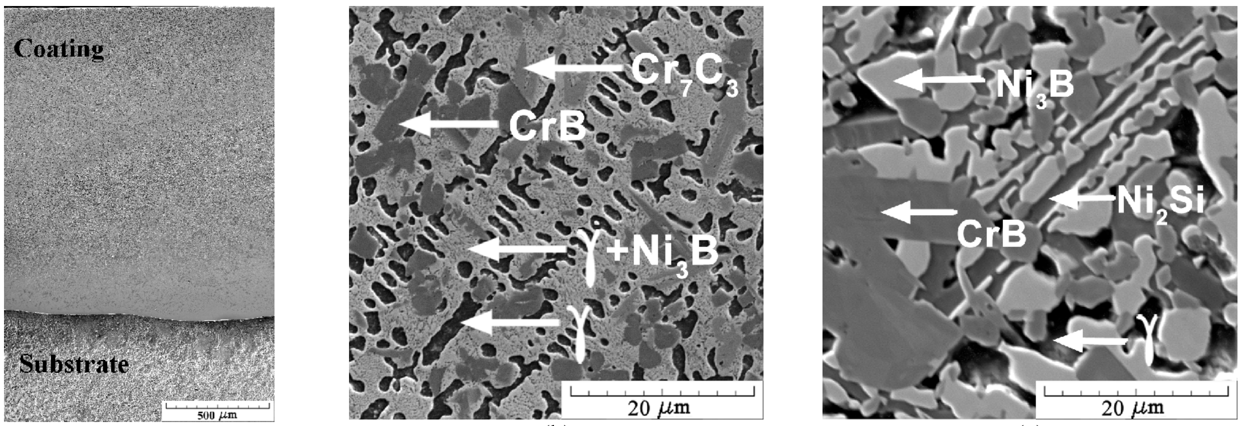
FIGURE 1. Pin-on-disk test scheme

The wear intensity I_h was calculated by the formula $I_h=Q/(\rho \cdot S \cdot L)$, were Q is specimen mass loss, g; ρ is specimen material density, g/cm^3; L is friction path length, cm; S is the geometric contact area, cm^2. The friction coefficient f was determined as the friction force to normal load ratio. The linear wear was determined by the formula $I=Q/(\rho \cdot S)$.

EXPERIMENTAL RESULTS AND DISCUSSION

The clad NiCrBSi coating (Fig. 2a) is characterized by a fairly uniform distribution of the structural constituents across the thickness [8]. The metal base of the coating comprises a γ-Ni solid solution and eutectic consisting of a γ-solid solution and a Ni_3B phase (Fig. 2b) [4, 8]. It was found by X-ray spectrometry microanalysis, X-ray phase analysis [9] and microdurometry that chromium carbide Cr_7C_3 with a hardness of 1650-1800 HV and chromium boride CrB with a hardness of 1950-2400 HV are the main strengthening phases of the coating. The average microhardness of the coating is 990 HV 0.05.

Under heating to 1025 °C followed by slow cooling in a vacuum furnace, large CrB (Fig. 2c) and Cr_7C_3 particles appear in the structure of the laser coating, which form a highly strong wear resistant skeleton [4]. Besides, there appears a new phase, namely, nickel silicide Ni_2Si (Fig. 2c), which enters into the triple eutectic composition γ+Ni_3B+Ni_2Si. After annealing at 1025 °C for 2 hours with slow cooling in a vacuum furnace, the average microhardness of the coating is 1050 HV 0.05.



(a) (b) (c)

FIGURE 2. The microstructure of the NiCrBSi coating after laser cladding (a, b) and after combined processing including laser cladding and annealing at 1025 °C (c)

Table 1 presents results of tribological pin-on-disk testing of the NiCrBSi coating after laser cladding and combined laser heat treatment including laser cladding and annealing at 1025 °C (2 h holding) followed by cooling in a vacuum furnace, the tests being performed under conditions of dry sliding friction in air.

TABLE 1. Mass loss *Q*, wear intensity I_h, linear wear *I*, friction coefficient *f* and average temperature in the surface layer *T* for coated NiCrBSi specimens in testing for sliding friction on a steel disk at various testing speeds *V* and testing times *t*

Coating state	*V*, m/s	*t*, min	*Q*, mg	I_h, 10^{-8}	*I*, mm	*f*	*T*, °C
Laser cladding	6.1	22	273.9	8.30	0.669	0.28	920
Laser cladding + annealing at 1025 °C	6.1	22	149.7	4.54	0.365	0.30	890
Laser cladding	9.3	9.5	275.3	12.74	0.672	0.20	>1000
Laser cladding + annealing at 1025 °C	9.3	9.5	150.0	6.94	0.366	0.25	>1000

The average volumetric temperature in the surface layer is seen to reach 890 °C and above in the high-speed tests. The mass loss, wear intensity and linear wear of the specimens with coatings after combined processing decrease by a factor of 1.8 from the respective characteristics of the clad coating in tests at speeds of 6.1 and 9.3 m/s. Consequently, additional high-temperature annealing of the clad coating increases significantly the frictional heat resistance of the coating, i.e. it offers a higher wear resistance under considerable frictional heating, despite the comparable values of microhardness for the laser-clad coatings and those after combined processing.

Besides, it follows from the table that the combined processing decreasing wear intensity causes no improvement of the antifriction properties of the clad coating; namely, a lower friction coefficient *f* is not reached, vice versa, the annealed coating demonstrates even a slight increase in the average friction coefficient. Note that, in all cases, the wear intensity of the NiCrBSi coating (see the table) is characterized by values an order of magnitude lower than those in the case of catastrophic heat-induced seizure of carbon steels after laser or bulk hardening under testing in air at speeds of 3.7 to 4.5 m/s, when the temperature of the surface layer is at most 550-700 °C [10, 11]. This testifies to increased wear resistance under considerable frictional heating of the NiCrBSi coating produced by laser cladding. Combined laser heat treatment (with annealing) offers an additional significant increase in the frictional heat resistance of the clad material.

The study of the friction surfaces testifies to the limitation of adhesive seizure and plastic edging on the wear surfaces of the additionally annealed specimens (Fig. 3). On these surfaces, under friction loading, there occurs "polishing out" of coarse strengthening phases, namely, borides CrB and carbides Cr_7C_3 (Fig. 3), which create a wear resistant skeleton on the friction surfaces, which hampers the evolution of heat wearing. Similarly, the wear-resistant skeleton formed by the carbide and boride phases on the NiCrBSi coatings during testing on a fixed abrasive makes a decisive contribution to the resistance of the coatings to abrasive wear [12].

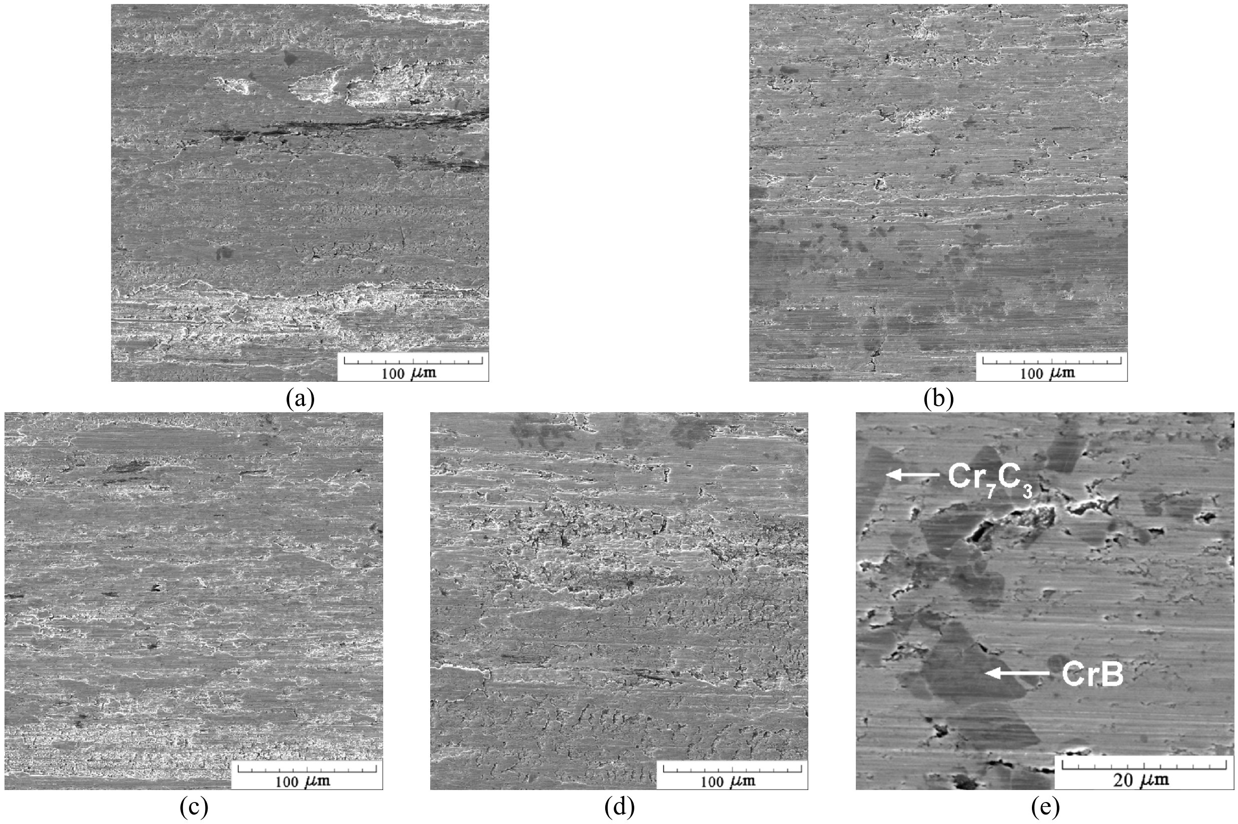


FIGURE 3. The wear surfaces of a laser-clad NiCrBSi coating (a, c) and that after combined processing including laser cladding and annealing at 1025 °C (b, d, e) after testing for sliding friction on a steel disk at speeds of 6.1 m/s (a, b) and 9.3 m/s (c-e)

CONCLUSION

The study pioneers in demonstrating that high-temperature (1025 °C) annealing of a NiCrBSi coating produced by gas powder laser cladding decreases wear intensity and linear wear by a factor of 1.8 under conditions of sliding friction in air at sliding speeds of 6.1 and 9.3 m/s, when the temperature of the frictional heating of the surface layer reaches ~900 °C and above. The increased wear resistance is caused by the formation of coarse strengthening phases (chromium borides CrB and chromium carbides Cr_7C_3 in the coating under annealing, which hamper the evolution of heat-induced seizure and plastic edging. Thus, combined laser heat treatment including laser cladding and high-temperature annealing increases the frictional heat resistance of the NiCrBSi coating.

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